Constraints on the time variation of the gravitational constant using gravitational-wave observations of binary neutron stars

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Background

The maximum and minimum allowed masses of neutron stars ($m_s^{\text{min, max}}$) at a particular cosmic epoch has a simple dependence on the value of $G = G_s$ at that epoch,

$$m_s^{\text{min, max}} = m^{\text{min, max}} \, (G_s/G_o)^{-3/2} \tag{1}$$

where G_o is the current value of G, and $m^{\text{min, max}}$ is the current value of minimum and maximum mass for the neutron stars.

Let m_o be the measured (redshifted) mass. The template matching condition gives,

$$m_o = \frac{G_s}{G_o} \left(\frac{1+z_s}{1+z_o} \right) m_s \tag{2}$$

where z_s is the true cosmological redshift of the source and z_o is the estimated redshift, say, from an electromagnetic observation.

Using the above equations, we can derive the bounds within which the observed masses should lie,

$$m_o^{\text{max, min}} = m^{\text{max, min}} \, (G_s/G_o)^{-1/2}. \tag{3}$$

That is, when $G_s \neq G_o$, the allowed range of measured neutron star masses will be different from the range m^{min} — m^{max}. If G_s has a significant deviation from the current value G_o, the observed values of neutron star masses would have gone out of the allowed range of neutron star masses. Hence such large deviations are ruled out by current GW observations. This is illustrated in Figure [2].

Results

- When $G_s \lesssim 4 \times 10^{-3} G_o$ or when $G_s \gtrsim 9 G_o$, the observed mass range of the neutron stars in GW170817 will go out of the predicted mass range. Thus, the fractional deviation $\Delta G/G_o := (G_s - G_o)/G_o$ in gravitational constant is constrained to be:

$$\boxed{-0.996 \lesssim \Delta G/G_o \lesssim 8}$$

- If we know the time Δt elapsed between the merger and the GW observation, we can compute an average rate of change of the G during this period: $\dot{G}/G_o \simeq \Delta G/(G_o \Delta t)$. For GW170817, we infer:

$$\boxed{-7 \times 10^{-9} \text{ yr}^{-1} \lesssim \dot{G}/G_o \lesssim 5 \times 10^{-8} \text{ yr}^{-1}}$$

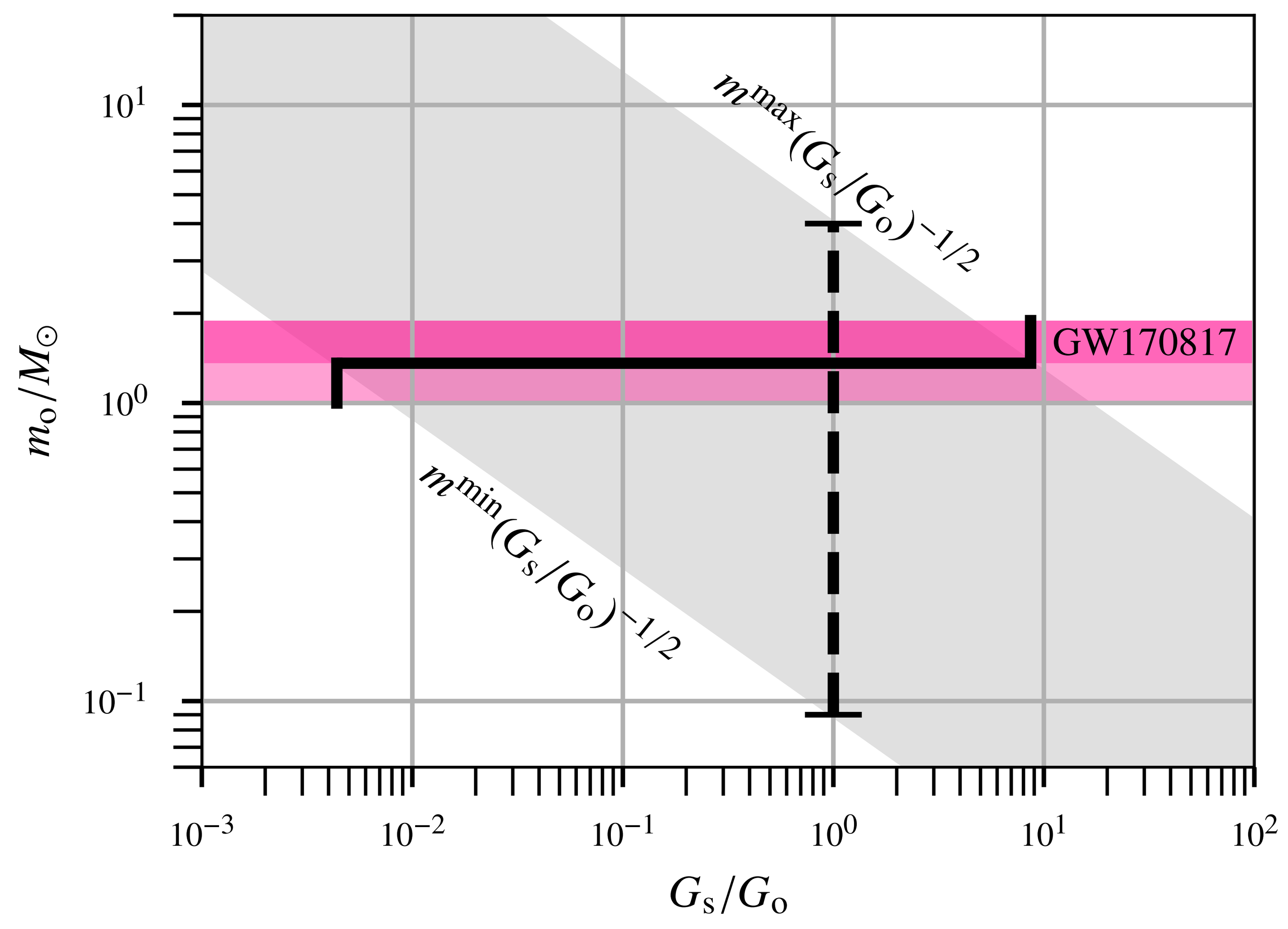

Fig. 2: *The horizontal axis corresponds to the assumed value of $G = G_s$ (in units of the current value G_o) at BNS merger epoch, and the vertical axis corresponds to the measured value of the neutron star mass m_o (in units of $M_\odot$). The horizontal patches correspond to the measured value of the neutron star masses from GW170817 (90% credible regions; the dark shade corresponds to primary mass while the light shade corresponds to secondary mass). The vertical dashed lines correspond to the theoretically allowed range of neutron star masses $m^{\text{min}} - m^{\text{max}}$ at the current epoch. The tilted gray regions show the allowed range of the observed neutron star mass (eq. [3]). The horizontal error bars show the constraints on G_s/G_o that we obtain by requiring that the measured values overlap with the theoretically allowed (gray) region.*

Summary and Future Directions

- Although our constraints are not as tight as the best available bounds from other measurements, they sample a different cosmological epoch that is not covered by other observations.
- Gravitational-wave observations sampling the extremes of the neutron star masses will further tighten these bounds.
- Additional detections of binary neutron stars would constrain the variation of G at different epochs. Projected constraints from third-generation GW detectors are shown in Figure [1].

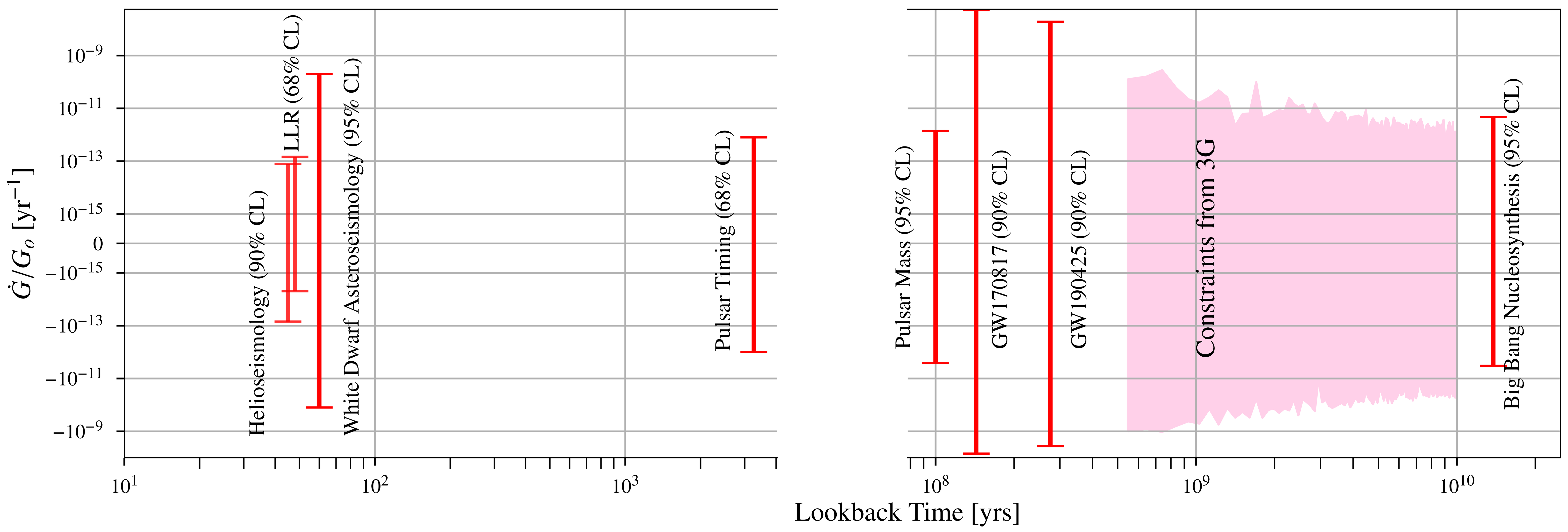

Fig. 1: Comparison of the constraints on $\dot{G}/G_o$ obtained from various observations with confidence levels of the constraints indicated in brackets (LLR denotes constraints from lunar laser ranging). The horizontal axis shows the look back time. The constraints presented this paper are labeled as GW170817 and GW190425, while the expected constraints from 10 year of observations with third-generation (3G) GW detectors is shown by the pink band.